The TEVA Experiment Cruise Report

by Peter H. Dahl, Darrell R. Jackson, and Kevin L. Williams

Technical Memorandum
APL-UW TM 1-95
March 1995

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ABSTRACT

A team from APL-UW made monostatic reverberation and bistatic forward scattering measurements in a shallow-water channel (depth 25.6 m) located within the Dry Tortugus collection of islands (24°36.7′N 82°50.7′W) during the period 9–17 February 1995. Accompanying the acoustic measurements were continuous measurements of wind speed and surface wave spectra, including wave directional information. The data will be used for sonar model development and model/data comparisons and in underwater system design, development, and performance predictions. The experiment, called the Torpedo Environmental Acoustic (TEVA) experiment, was conducted in conjunction with the Coastal Benthic Boundary Layer (CBBL) experiment organized by the Naval Research Laboratory, whose focus included measuring the geoacoustic and acoustic properties of the sea bed. The detailed environmental characterization afforded by combining assets of both the TEVA and CBBL experiments will also allow rigorous comparisons of acoustic models and measurements.

Contents

List of Figures

1. INTRODUCTION

This report describes work carried out by a team from APL-UW while aboard the RV *Seaward Explorer* to conduct the Torpedo Environmental Acoustic (TEVA) experiment in February 1995. The focus of the TEVA experiment was on the relationship between the environment (defined by sea surface and sea bottom characterizations) and acoustic propagation and scattering in the weapon frequency range. Our results will be used to develop new models, to improve existing models, and in underwater system design, development, and performance predictions.

This report summarizes the acoustic and environmental measurements made during the TEVA experiment, presents some examples of preliminary data analysis, and outlines pathways for future data analysis.

The following objectives of the TEVA experiment were achieved:

1. Measure the scattering function of the shallow-water, multipath channel of Dry Tortugus, by probing this channel with waveforms of large time-bandwidth (TW) products. The scattering function $R_s(\tau, \phi)$ is a measure of the average delay, or time spread, (τ) and frequency spread (ϕ) that a transmitted signal will be subjected to by the underwater channel.

2. Measure single-bounce scattering characteristics in forward scattering (i.e., separate surface and bottom bounce paths). Characteristics include time, frequency, and spatial coherence.

3. Measure the surface backscattering strength (monostatic configuration) and the scattering function for shallow-water reverberation.

4. Characterize the sea surface environment through continuous measurements of wind speed and directional wave spectra.

The TEVA experiment was carried out in conjunction with the Applied Physics Laboratory's participation in the Coastal Benthic Boundary Layer (CBBL) experiment. The CBBL experiment, organized by NRL, was a multi-organization experiment whose focus was on properties of the benthic boundary layer, particularly the genesis of these properties under physical and biological forcing, and the resultant acoustic and geoacoustic behavior. APL's participation in this experiment is summarized in a separate cruise report.

The ONR Torpedo Environments Project funded design of and preparations for TEVA, funded design and fabrication of experimental components such as the shallow-water spar buoy, and contributed, along with CBBL funding, to chartering costs for the *Seaward Explorer* and to APL personnel costs.

2. TEVA EXPERIMENTAL SCHEDULE

1–6 Feb 95	APL-UW loadout on the *Seaward Explorer*, Key West Naval Air Station (NAS)
7 Feb	*Seaward Explorer* departs Key West en route to experiment site (24°36.7′N 82°50.7′W)
8 Feb	Four-point mooring and buoy deployments
9-17 Feb	TEVA measurements
18 Feb	*Seaward Explorer* transits to Key West NAS; APL-UW offload completed
19 Feb–1 Mar	*Seaward Explorer* redeployed for TTCP bottom scattering experiment with U. K.

3. EXPERIMENTAL DESCRIPTION

The experiment was conducted off the island of Garden Key, within the collection of islands known as Dry Tortugas (24°36.7′N 82°50.7′W). The water depth was 25.6 m, and the bottom consisted of calcium shell deposits and soft mud. Further details on bottom properties are included in the CBBL cruise report.

The *Seaward Explorer* was placed in a four-point moor, with ability to vary the length of the mooring lines attached to the four mooring buoys. The TEVA acoustic measurements—bistatic forward propagation and scattering and monostatic reverberation—were made from the vessel's stern, with care taken to avoid acoustic scattering from the mooring lines or buoys.

4. ENVIRONMENTAL MEASUREMENTS

Wind speed measurements were made using a propeller vane anemometer mounted 6.9 m above the sea surface at the top of the hydraulic U-frame located at the stern end of the *Seaward Explorer*. This location resulted in minimal interference from vessel structures. Wind speed was recorded continuously as a 5-minute average every 10 minutes. The record includes both scaler-average and vector-average wind speeds and their standard deviations and wind direction and its standard deviation. A summary of the wind speed over the duration of the experiment is shown in Fig. 1.

Occasional gaps in the record occur at the beginning of the experiment owing to power interruptions (though not during any of the acoustic measurements). This problem was later solved.

Surface wave displacement spectra, including directional information, were measured using a Datawell Directional Waverider buoy.[1] The buoy was moored approximately 200 m from the *Seaward Explorer*, and data were radio transmitted back to the vessel every hour. Two surface displacement spectra, taken one hour apart, are shown in Fig. 2. The spectrum taken at 12:40 shows a developing wind-wave spectral peak, consistent with the wind speed having increased from 3.3 to 4.3 m/s over the previous hour. The wind direction was 140°, as was the direction associated with the wind-wave peak at approximately 0.5 Hz shown in the 12:40 spectrum. Both spectra also show a swell peak at approximately 0.1 Hz, with swell wave energy coming from the south. The wave directional information will be used to evaluate assumptions regarding isotropic scattering in sonar models.

Conductivity, temperature, pressure (CTD) measurements were made approximately every 3 hours using a Sea-Bird CTD. Figure 3 shows a typical CTD cast. The the conditions were nearly isovelocity, and in the preliminary results presented below we have assumed a constant sound speed of 1520 m/s.

5. ACOUSTIC MEASUREMENTS

5.1 Monostatic Reverberation

Total reverberation (surface + bottom + volume) measurements in shallow-water conditions were made with a modified Mk 46 array suspended at depths between 5 and 12 m and set at pitch angles (positive with respect to horizontal) between 3 and 20°. The array is divided into four subapertures; data were recorded on four channels by transmitting on the sum beam and receiving on the individual subapertures. At 30 kHz the array's sum beam width between –3 dB points is approximately 15° and 20° for the narrow and wide beams, respectively. For the TEVA measurements, the wide beam was set vertical and narrow beam was set horizontal. For each ping, we recorded the array's pitch angle, depth, and compass direction.

The signal waveforms used in the acoustic measurements (both reverberation and forward propagation) are listed in Table 1. The gc (Golomb-Costas) and wc (Welch-Costas) waveforms (known as Costas codes) were generated using a software tool kit

[1]The Datawell buoy was leased from Coastal Leasing Inc., Cambridge, MA.

developed by Rickard.[2] Software made available by J. Luby, APL-UW, was used to generate the FM, AP, and AC waveforms given in Table 1. Measurements made with the coded waveforms can be used for estimating the scattering function, in addition to being used as benchmark examples for comparisons with reverberation simulation models.

Table 1. Signal waveforms used in TEVA experiment. Costas codes gc and wc consist of 27 chips, except for gc3200b and gc6200b, which consist of 9 chips. Further information on signals AP and AC is available from P. H. Dahl, APL-UW.

Signal Waveform ID	Freq., kHz	Bandwidth, kHz	Pulse Length, ms
CW	30	1	1
FM	27	6	40
gc3200	30	3	200
gc3200b	30	3	200
gc6200	30	6	200
gc6200b	30	6	200
gc3400	30	3	400
wc3200	30	3	200
wc6200	30	3	200
AP	–	–	–
AC	–	–	–

Measurements made with the more simple CW waveform will be used to estimate the surface backscattering strength (SBSS). For example, Fig. 4a shows the relative reverberation level vs time for run B130 during which the wind speed was approximately 5 m/s. Figure 4b (solid line) shows the estimated arrival angle computed using the phase difference between the upper and lower halves of the Mk 46 array, and the expected arrival angle for surface scattering (circles), based on straight-ray (nonrefracted) propagation.[3] The overlap between the expected and the estimated arrival angles in the vicinity of 25 to 60 ms (10° to 40°) confirms that this time segment of the reverberation originates from the sea surface.

[2]Rickard, Scott, "Large Sets of Frequency Hopped Waveforms with Nearly Ideal Orthogonality Properties," M. S. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1993.

[3]Refraction effects are minimal in this case because of the the nearly isovelocity conditions.

The data in Fig. 4 can be converted to backscattering strength estimates upon accounting for calibration constants, beam pattern effects, and propagation loss (Fig. 5). The angular range for which reliable estimates are made is reduced in this case to between 16° and 30° because of beam pattern effects. (This range may be extended upon further analysis.) It is noteworthy, however, that the estimates shown in Fig. 5 are relatively independent of angle.

Measurements of the type shown in Figs. 4 and 5 were made daily between 9 and 15 February, totaling 125 runs. All signal types listed in Table 1 were used in these measurements. The measurements were made at grazing angles between 5° and 30° (preliminary estimates of minimum and maximum grazing angles) and at wind speeds between 1 and 6 m/s. This wind speed range represents one of the most vexing problems in high-frequency sonar modeling. In order to study the wind speed vs SBSS relationship in detail, a 24-hour experiment was designed wherein reverberation measurements were made every 1/2 hour starting 10:00 on 14 February.

5.2 Bistatic Forward Propagation and Scattering

A sketch of the geometry used in the bistatic forward propagation scattering measurements is shown in Fig. 6. The focus of these measurements was on the multipath propagation and scattering that occurs in shallow water and involves both surface and bottom interactions. Note that during the first two days of the experiment, surface bistatic scattering measurements were made using a combination of the BAMS directional source and the APL bistatic receiver (Fig. 6). Upon completion of these measurements, the BAMS source was redirected toward the bottom to begin the CBBL bottom scattering measurement program.

The remainder of the TEVA bistatic measurements were made using the spar buoy source. Signals were transmitted from one of two ITC-1032 transducers suspended from the spar buoy at depths of 7.7 and 17.2 m. The spar buoy was tethered to the *Seaward Explorer* by a 400-m-long electromechanical cable. Transmissions using the signals in Table 1 were recorded on eight elements of the horizontal line array (the elements were spaced logarithmically across the 84-cm-long array).

Measurements were made at ranges between 70 and 250 m. For the shorter ranges, the surface and bottom-bounce paths are readily distinguished when using the short (CW) signal from Table 1. This is shown in Fig. 7, where the range is 73 m and the surface and bottom bounce paths are well separated using the 1-ms CW pulse. The wind speed was approximately 5 m/s, and the surface bounce path with grazing angle $\theta \approx 13°$ has undergone measurable time spreading which will affect the frequency coherence. The reduced level of the surface path compared with the direct path may be explained by bubble attenuation. Note that the bottom grazing angle ($\theta \approx 21°$) is

well above the critical angle ($\approx 8^\circ$) that would be expected for this type of sea bed, which would account for the attenuation (in excess of 20 dB) seen for the bottom-bounce path.

Figure 8 shows the matched filter output (for the zero-Doppler axis) for two runs made with the 200-ms-long gc6200 signal. An example of the received spectrum for this signal is shown in Fig. 9. The range for these runs is approximately 105 m, and the wind speed was less than 2 m/s. Referring to Fig. 7, the solid line shows run L066 which used the deep (17.2 m) spar buoy source, and the dashed line shows run L067 which used the shallow (7.7 m) spar buoy source. The runs were made sequentially within 2 minutes of each other. The peaks at A are from the direct arrivals for each run. The peak at B shows the surface-bounce arrival for run L067 which had a nominal grazing angle θ of 8°. The peak at C shows the surface-bounce arrival for run L066 which had a nominal grazing angle θ of 13°. These arrivals are nicely resolved from the direct path, indicating the sea surface has not disrupted the phase structure of the 200-ms-long pulse. The bottom-bounce arrivals, expected at a 2.2-ms delay with $\theta \approx 14^\circ$ and a 3.9-ms delay with $\theta \approx 19^\circ$ for runs L066 and L067, respectively, will be severely attenuated and are not detected in this processing. (It is possible that the peak just to the right of C is the bottom arrival delayed at 2.2 ms.)

Finally, the peaks at D are the result of the autocorrelation function of signal gc6200 having a significant nonzero value at this delay. These peaks are repetitions of the direct arrivals for each run. The autocorrelation function for the transmit signal is equivalent to the zero-Doppler axis of the signal's ambiguity function. By combining measurements that used signal waveforms with differing properties in their ambiguity function, we can expect to reconstruct estimates of the scattering function.

Measurements of the type shown in Figs. 7 and 8 were taken daily between 11 and 17 February, with the exception of 14 and 15 February, totaling 97 runs.

6. SUMMARY AND PROPOSED DATA ANALYSIS

We achieved our principal measurement objective of making measurements of (1) monostatic reverberation and (2) bistatic forward propagation and scattering in shallow-water conditions. Preliminary analysis of the data has confirmed its overall quality. Below is a proposed outline for a more complete analysis of the TEVA data base.

1. Estimate the surface backscattering strength (SBSS). Determine the relation between these estimates and wind speed and wave direction with respect to scattering direction. Use the data to confirm the angular dependence of SBSS in the $5-30°$ range. Data from the 24-hr experiment will be especially valuable for determining correlations with wind speed.

2. Estimate the surface bistatic scattering strength from the smaller data set on bistatic surface scattering taken during the early part of the experiment.

3. Estimate the scattering function (and related coherences) for monostatic reverberation in shallow-water conditions, using data taken with the long (coded) signals in Table 1. Reconstruct independent estimates of the scattering function based on the isolated surface and bottom backscattering measurements made with short (CW) signals during both the TEVA and CBBL experiments.

4. Estimate the scattering function (and related coherences) for bistatic forward propagation and scattering in shallow-water conditions, using data taken with the coded signals from Table 1. It may also be possible to construct an alternative estimate of the scattering function using data taken with the short (CW) signals and at short ranges.

The scattering function depends on the acquisition geometry, e.g., the number of surface and bottom bounces, and environment. Models that predict isolated scattering, e.g., surface backscattering, are referred to as component models. Our goal in parts (3) and (4) is to construct realistic bounds on the scattering function as a function of both geometry and environmental conditions through synthesis of component sonar models and to compare these bounds with actual measurements of the scattering function.

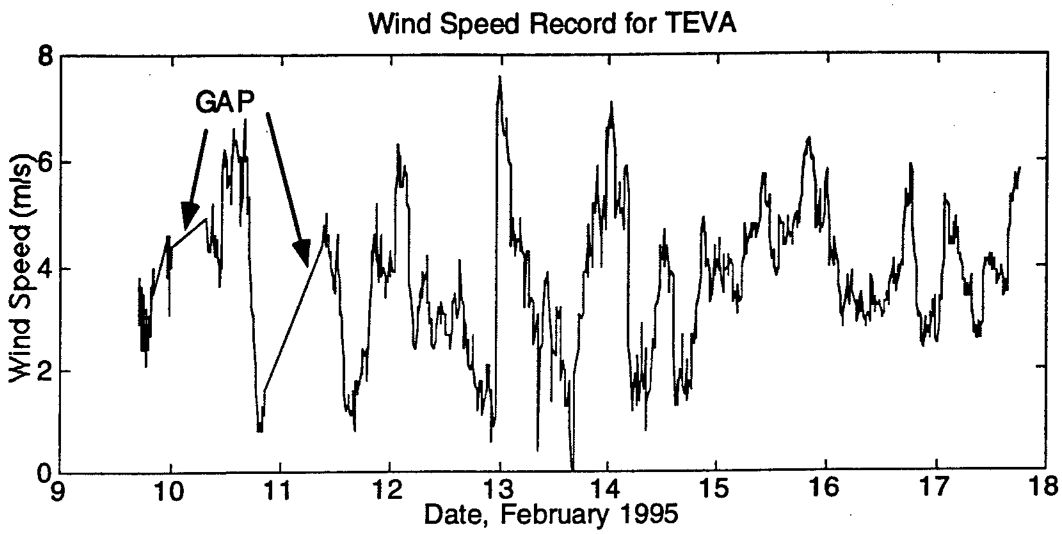

Figure 1. Time series of wind speed for the duration of the TEVA experiment. Two gaps in the wind speed record are noted.

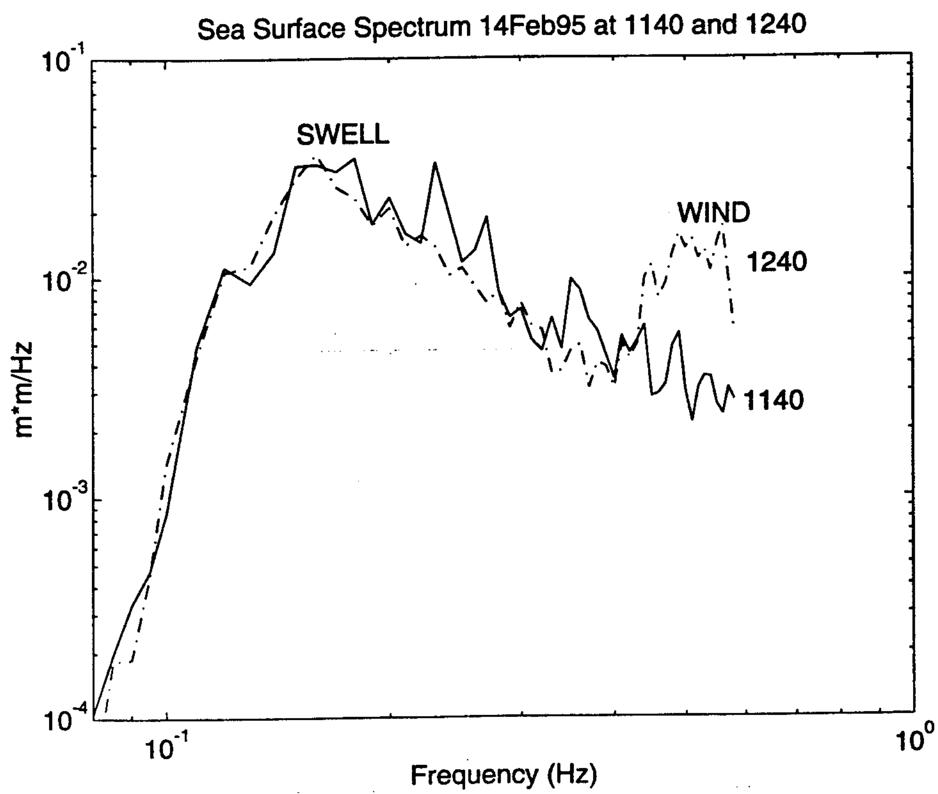

Figure 2. Sea surface displacement spectra taken 1 hour apart. The spectrum taken at 12:40 shows a developing wind-wave spectral peak, consistent with the wind speed having increased from 3.3 to 4.3 m/s over the previous hour. The wind direction was 140°, as was the direction associated with the wind-wave peak at approximately 0.5 Hz shown in the 12:40 spectrum. Both spectra also show a swell peak at approximately 0.1 Hz, with swell wave energy coming from the south.

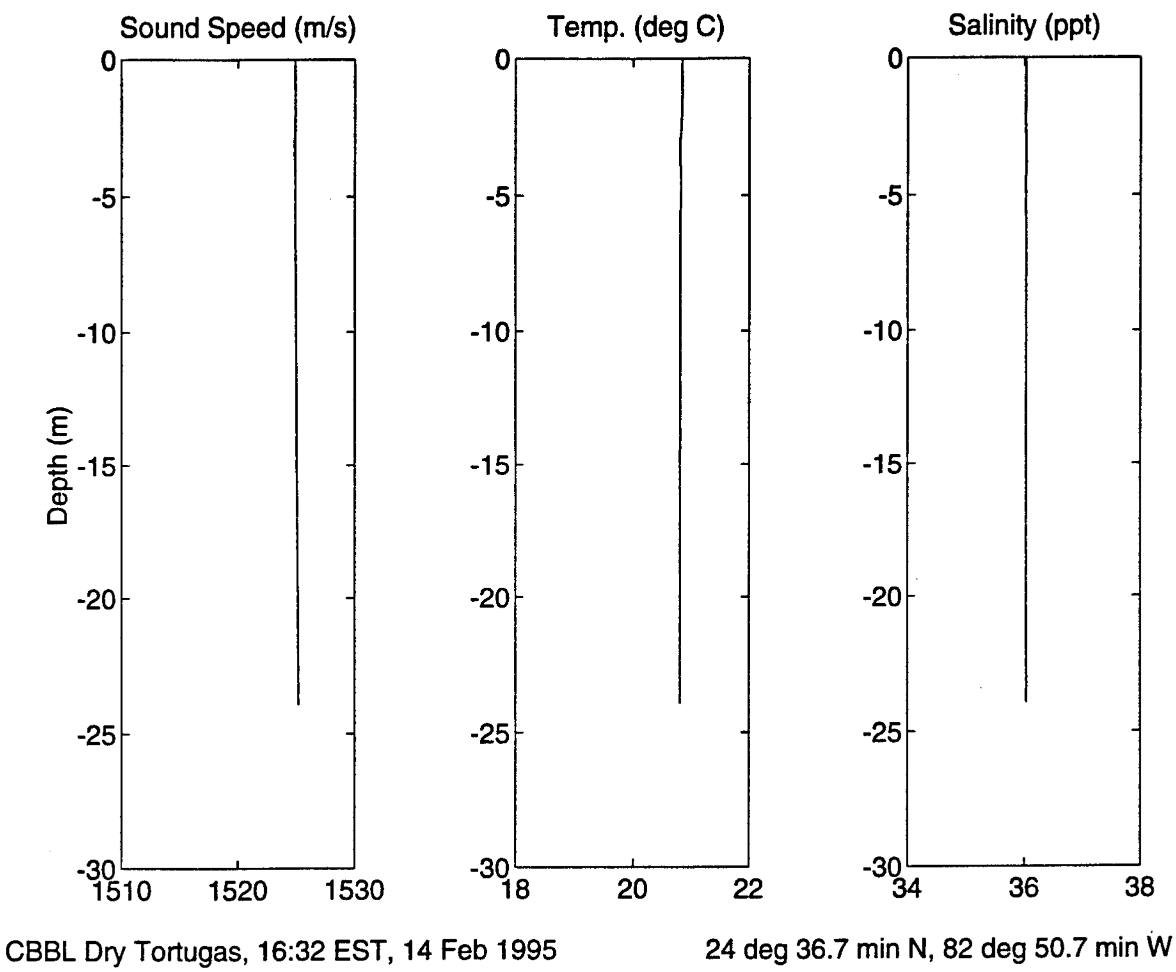

Figure 3. Typical CTD cast taken during CBBL and TEVA experiments.

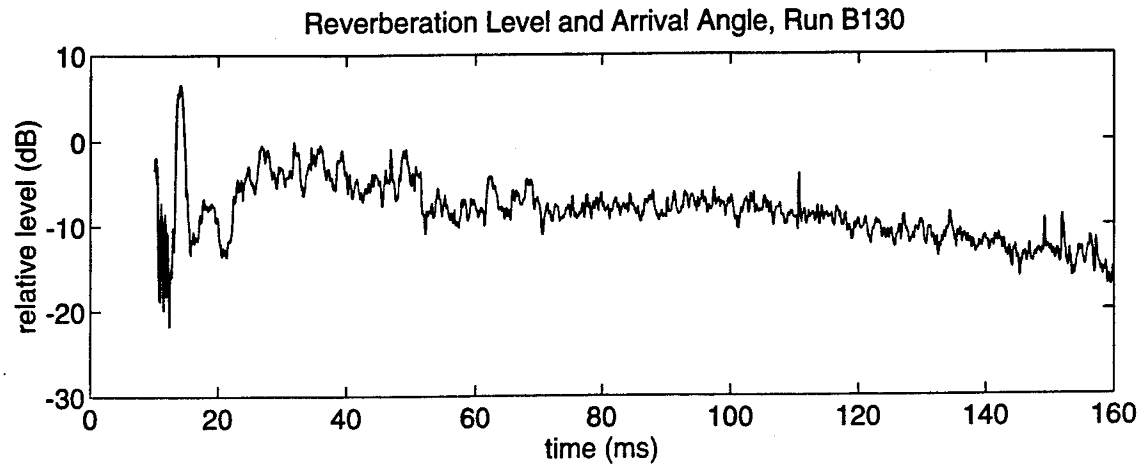

Figure 4a. Reverberation level (in arbitrary decibel units) vs time for run B130.

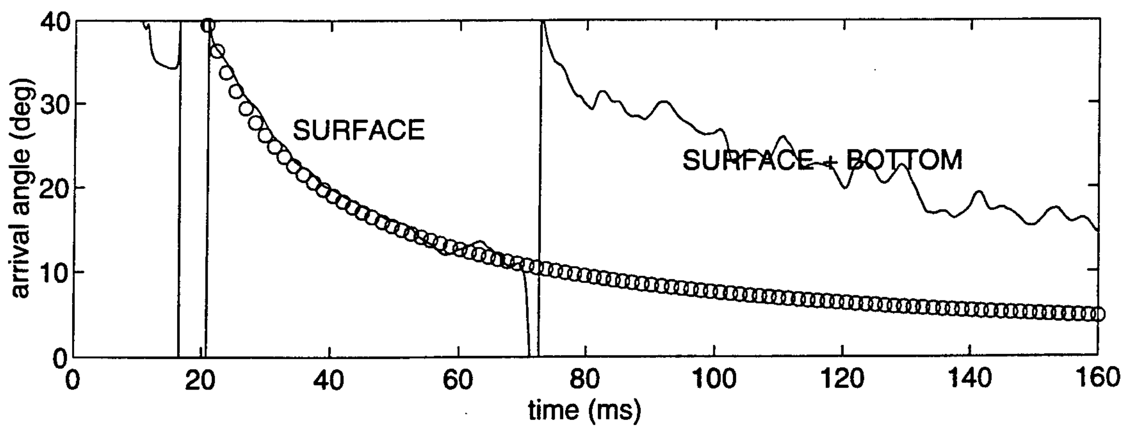

Figure 4b. Arrival angle vs time for the reverberation shown in Fig. 4a. Solid line shows angle estimated using the phase information from the array; circles show angle estimated from ray theory assuming that the reverberation originates from surface alone. This assumption breaks down at about 70 ms.

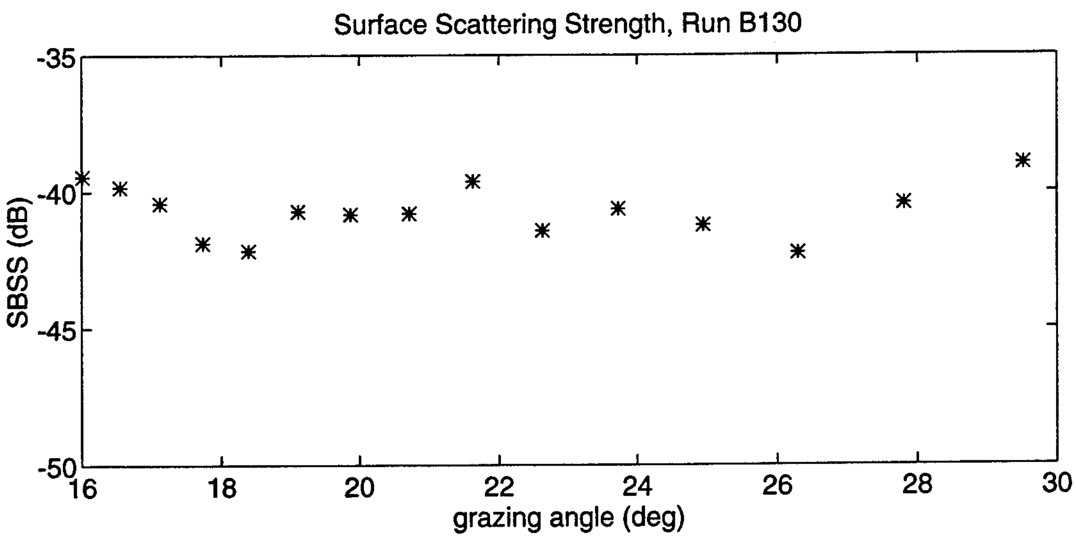

Figure 5. Surface backscattering strength estimate from the data in Figs. 4a and 4b (run B130). The wind speed is approximately 5 m/s.

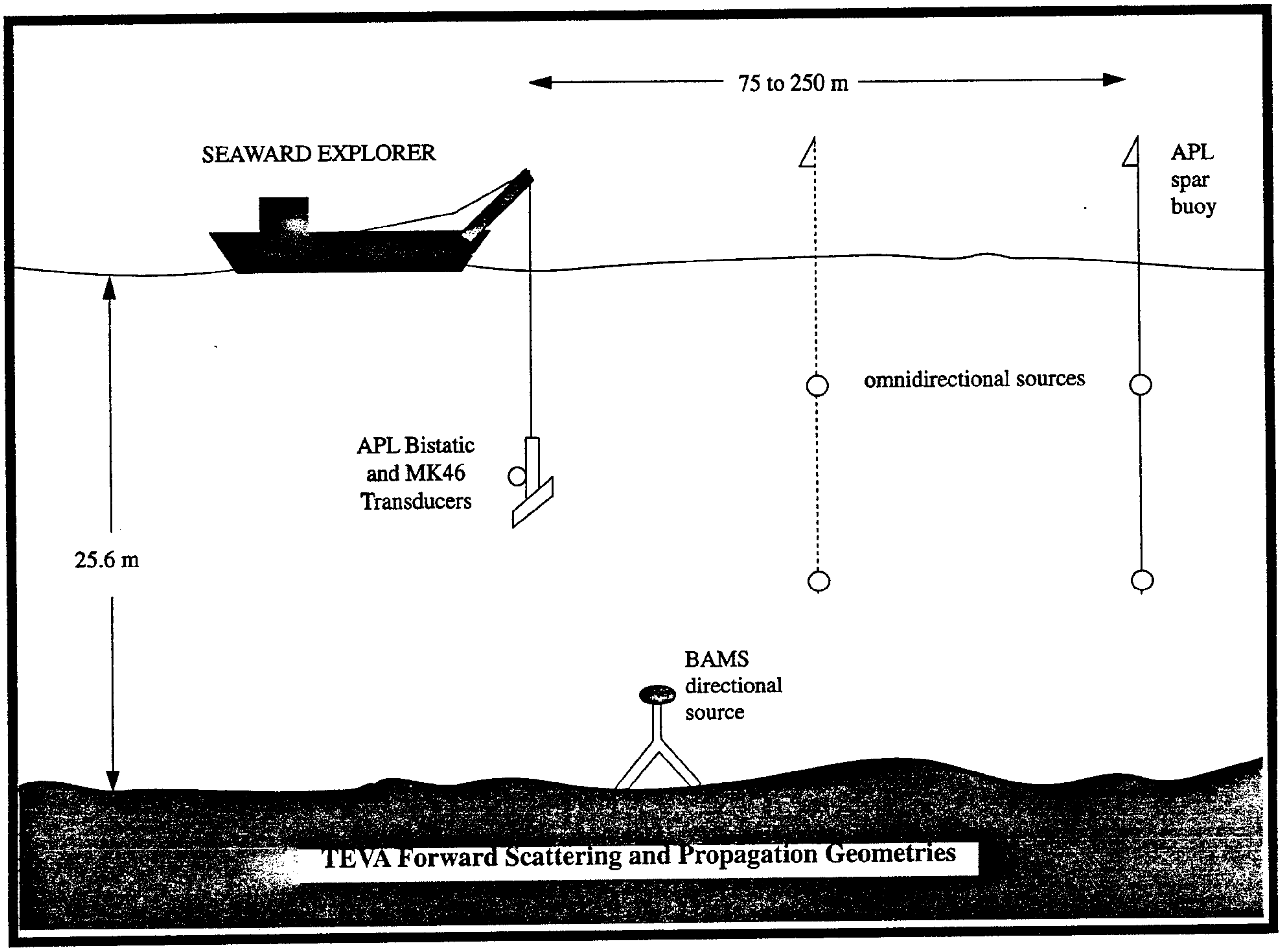

Figure 6. Sketch of the geometry used in the bistatic forward propagation and scattering measurements.

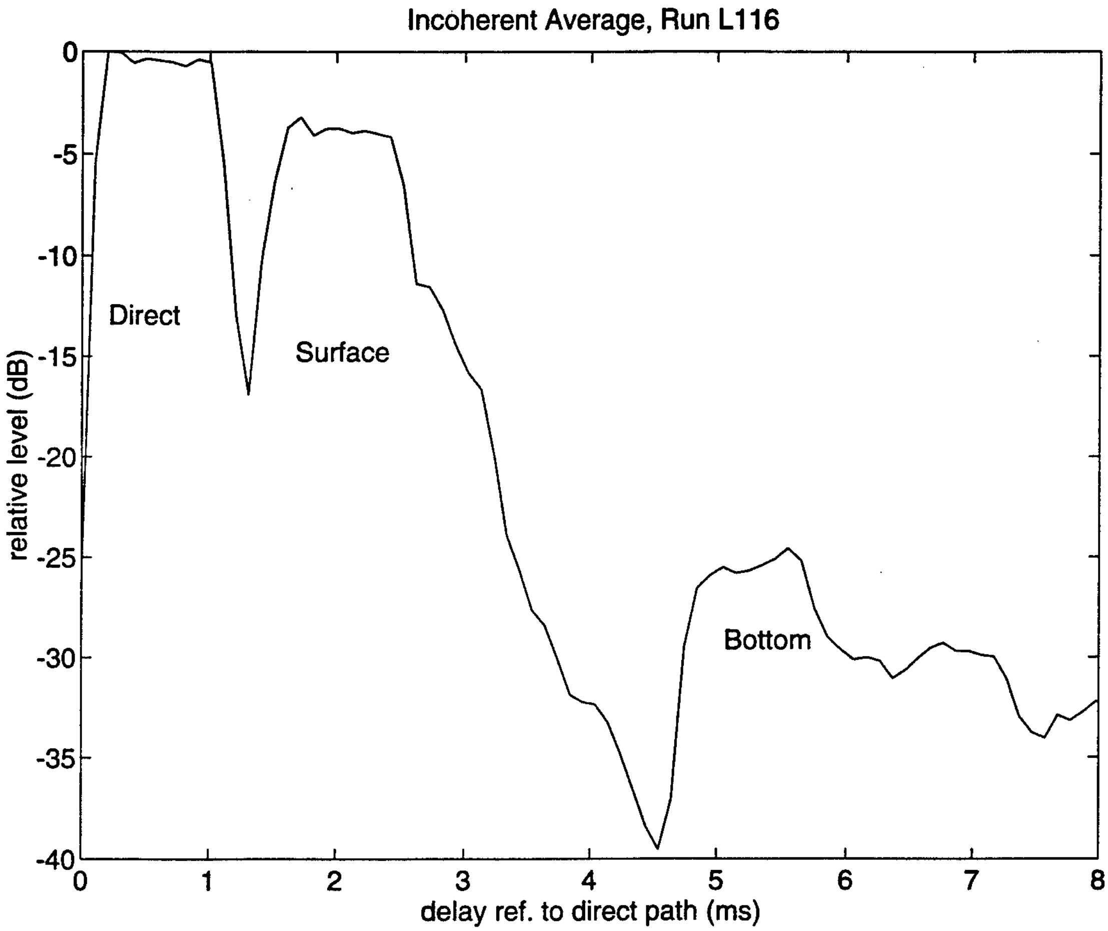

Figure 7. Bistatic forward scattered intensity vs time for run L116 and element #1 of the horizontal array. The direct, surface, and bottom-bounce paths are readily distinguished with the 1-ms CW probe signal. Note that the bottom grazing angle ($\sim 21^o$) is well above the critical angle ($\sim 8^o$) expected for this type of sea bed, which would account for the attenuation (in excess of 20 dB).

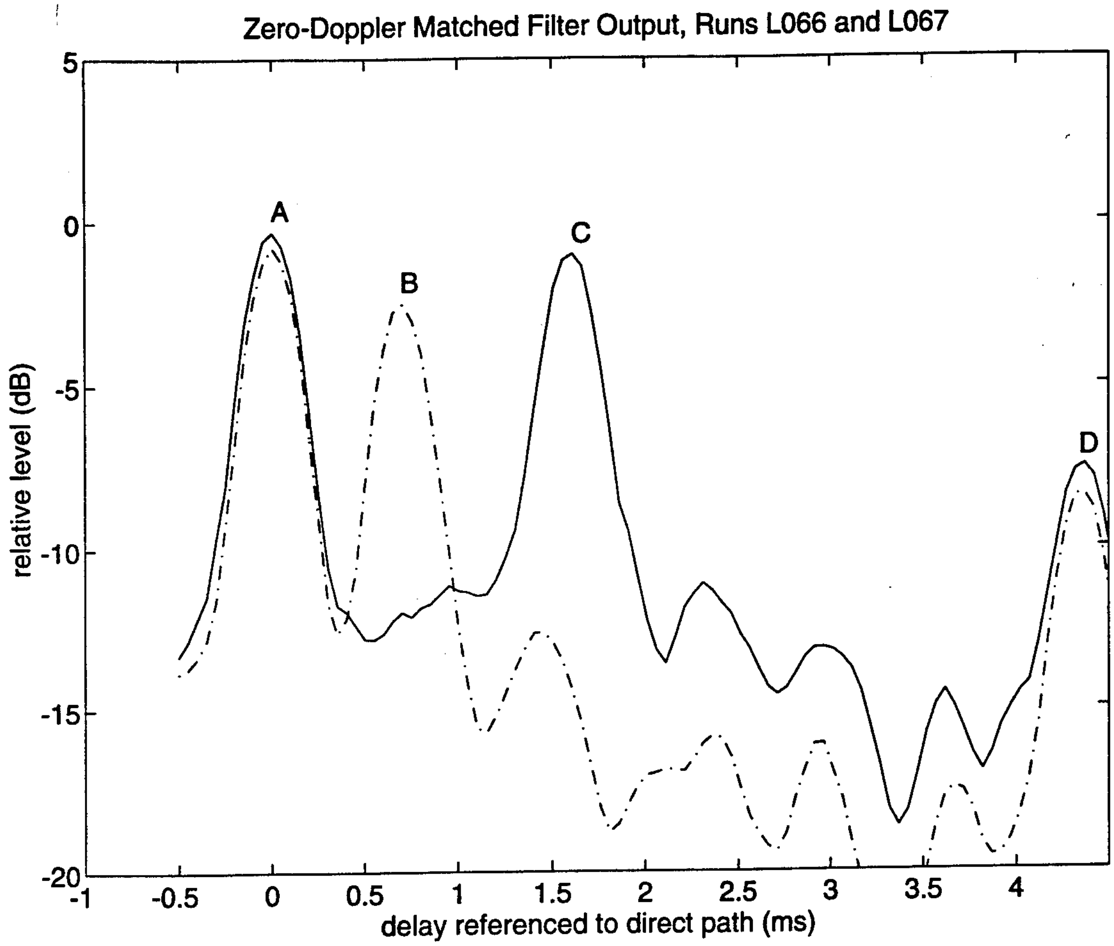

Figure 8. Matched filter output (for the zero-Doppler axis) for two runs made with the 200-ms-long gc6200 signal. The solid line shows run L066 which used the deep (17.2 m) spar buoy source, and the dashed line shows run L067 which used the shallow (7.7 m) spar buoy source. The peaks at A are from the direct arrivals for each run; the peak at B shows the surface-bounce arrival for run L067 which had a nominal grazing angle θ of 8°, and the peak at C shows the surface-bounce arrival for run L066 which had a nominal grazing angle θ of 13°. The peaks at D are a result of the autocorrelation function of signal gc6200 having a significant nonzero value at this delay.

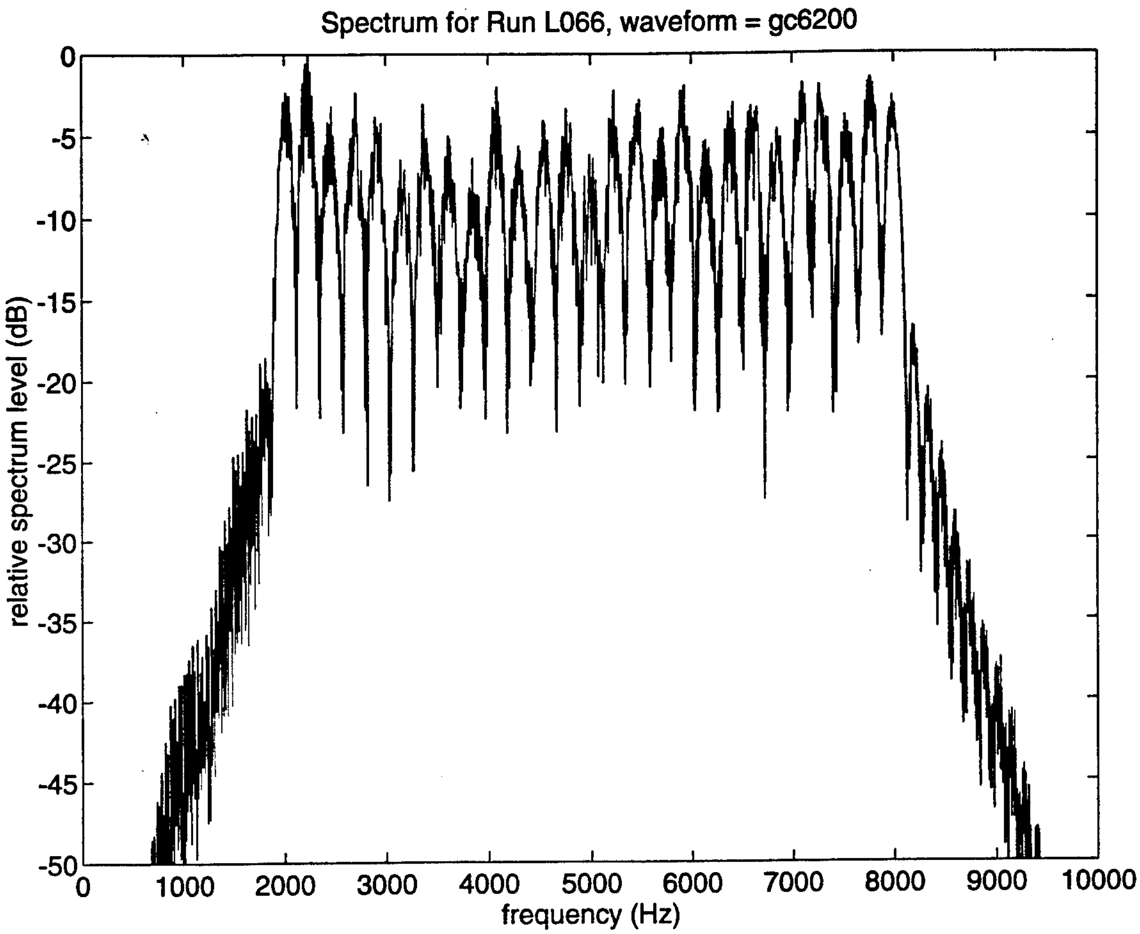

Figure 9. Received spectrum for transmitted signal gc6200.

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13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
Monostatic reverberation, bistatic forward scattering, shallow-water channel, environmental acoustics, scattering function

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